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ABSTRACT

The hypothesis as to the atomic structure of any given substance is introduced in many physics and chemistry textbooks by conveying the idea of repetitive division of a given amount of substance, for example, by grinding, dissolving, or evaporating. The rationale for this approach is the assumption of students inferring that this process of subdivision cannot be executed idenfinitely; that is, that there exist smallest possible subdivisions which in turn constitute the discontinuous structure of the undivided substance. Classroom conversations and interviews were conducted on the diffusion of ether and on the effect of changing the volume of a given portion of air upon temperature change. Empirical findings show that, on the one hand, many students (N=49) assimilate easily the idea of dividing a substance into smallest particles when dissolving or evaporating it. On the other hand, only a few students seem ready to acknowledge these particles as preformed building blocks of matter. In this respect, the approach seems to be inadequate. Comparisons, drawings, and interpretations offered to students in the later sections of interviews are included in an appendix. (JN)

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The Atom - The Final Link in the Division Process or the First Building Block?

Pre-instructional Conceptions about the Structure of Substances[+)]

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by

Helga Pfundt[++)]

Abstract

The hypothesis as to the atomic structure of any given substance is introduced in many textbooks of physics and chemistry by conveying the idea of repetitive division of a given amount of substance, e.g. by grinding, dissolving or evaporating. The rationale for this approach is the assumption of pupils inferring that this process of subdivision cannot be executed indefinitely, i.e. that there exist smallest possible subdivisions which in turn constitute the discontinuous structure of the undivided substance. Empirical findings show that, on the one hand, many students assimilate easily the idea of dividing a substance into smallest particles when dissolving or evaporating it. On the other hand, only few pupils seem ready to acknowledge these particles as preformed building-blocks of matter. In this respect the approach seems to be inadequate.

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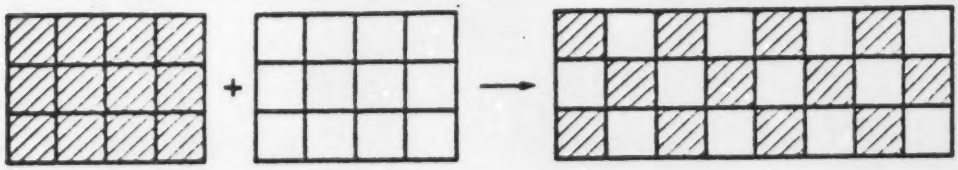
1. The Conception of the Atom as the Final Link in the Division Process

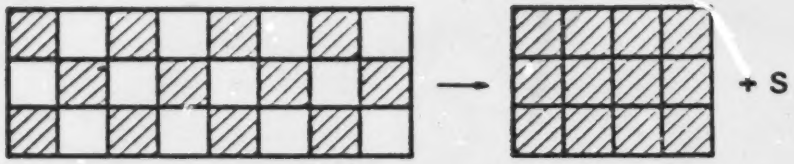
Dealing with certain aspects of pupils' conceptions of atoms was first prompted by several observations I made while teaching chemistry quite some time ago. I discussed the fundamental principles of the atomic hypothesis with pupils who had just transferred from the 10th grade of the "Realschule" (intermediate school) to the "Wirtschafts-oberschule" (secondary school emphasizing economic science). After I succeeded in diverting the pupils' attention from the mere repetition of particle and conversion symbols such as Fe + S → FeS to the conceptions behind these symbols, the pupils offerred representations such as the following:



Fe + S → Fe S

First the pupils drew pieces of iron and sulfur, which were continuously structured. Then, for conversion, they divided these continua into many small cubes - the atoms. They ordered these atoms in a regular pattern to form a piece of iron sulfide. I pointed out to the pupils that they had assumed the atoms *to be* cube-shaped. Their response was that they could probably also be right parallelepipeds. Probably, iron and sulfur atoms are also different in size. In any case, they would have to fit each other. It became clear later on that what was meant by "fit" was: "able to be joined without gaps".

Mentally, we went through the recovery of iron from iron sulfide. In the pictorial representation the pupils sorted the cube-shaped iron atoms out of the piece of iron sulfide and combined them without gaps to form a piece of iron:



Fe S ⟶ Fe + S

I tried to steer the conversation to the significance of the depicted boundaries in the piece of iron and pointed out the visible lines. The pupils said that, actually, the lines could be left out. The recovery of iron takes place under considerably great temperature. In that case, the individual particles would not remain separate anyway. I asked whether such a piece of iron, if converted again, would then be divided in completely different places - possibly even into any number of small pieces. The answer: in other places, probably, but not into any number of small pieces. After all, the resulting particles are so small that they cannot be divided any further. Substances are not infinitely divisible.

When this conversation is analyzed, several very interesting conceptions are uncovered. I was repeatedly confronted by variants of these conceptions from pupils.

Apparently, the pupils imagined that substances are continua. These continua are divided during conversion. Sometime in the course of continued division, particles are formed which are so small that they cannot be divided any further. These particles, however, are not already preformed in the substances. Accordingly, they can be fitted together again in such a way that the boundaries of the particles are erased, i.e. that continua are formed again.

It will have become clear to whomever is familiar with the history of the concept of the atom that the pupils expressed a conception that Aristotle brought to the concept and that played a central role in the discussion of the concept of the atom for many centuries: the notion of the limited divisibility of the *continuum*. Due to partly mathematical and partly physical considerations, Aristotle rejected the idea of Democritus and other philosophers that there exists something which is indivisible - the atoms - as well as a vacuum between them. He postulated that the space was continuously filled and that the division of the continuum potentially is infinite but that during actual division one arrives in the end at something which is indivisible - the atoms. The difficulty underlying this view was surpassed by the argument that the points at which division actually takes place are not directly one behind the other but interrupted by other points. Division can take place at any point, but at all points at the same time (K. LASSWITZ, 1963). The pupils with whom the conversation described above was conducted would essentially have agreed with this view.

The discussion of the concept of the atom gradually led to our modern conception when interest shifted from the question of a final link in the division process to the question of a first building block - when it was no longer a question of whether the continuum is infinitely divisible or not, but of whether substances are continuously or discontinuously structured (K. LASSWITZ, 1963; A.G.M. VAN MELSEN, 1957). The step from a continuum which is divisible within limits to a discontinuum composed of something which is indivisible had apparently not been taken by the pupils mentioned above even though they already worked with atomic and conversion symbols. This step, however, is crucial for the development of a productive concept of the atom. It is not so much the conception that given portions of substances are not infinitely divisible which is decisive, but that these smallest possible subdivisions are not the result of division but are preformed in the substances, i.e. are the discrete building-blocks of the substances.

2. Introduction to the Atomic Hypothesis in Some Chemistry Textbooks

How does the decisive step toward the conception of preformed particles look in science education? In the following I will single out four approaches to the atomic hypothesis which are taken up in many physics and chemistry textbooks and whose suitability I would like to question.

(1) The Approach via the Mechanical Division of Solids

The train of thought is the following: pieces of solids can be ground to form ever smaller grains. How far can these resulting grains be divided further? Is there a limit? At this point of instruction the pupils are told: there is a limit to divisibility. The smallest particles are called atoms.

The question here is whether the pupils really do comprehend the idea that the smallest particles do not first result from the division of substances (imagined to be continua), but that they are already preformed in the substances, i.e. that substances are discontinua.

(2) The Approach via the Dissolution of Solids

In the book "Atommodelle im Unterricht" (E. KIRCHER, A. TESSMANN, 1977, 19) in the chapter headed "The Hypothesis of Particles with regard to Liquids" it says:

"The experimental study of suspensions, colloids and true solutions can serve to make the particle structure of matter comprehensible to the pupil. In suspensions and colloid solutions particles with decreasing size are evidenced. In true solutions, however, no particles can be evidenced with the methods used in the course of instruction. The particle model cannot, therefore, be won directly from the experiments. The series of experiments, however, lends plausibility to the hypothesis that matter is made up of minute particles."

This series of experiments certainly does not make it plausible that the liquid substances in which particles of solids are evidenced or presumed are made up of (preformed) particles. It can, perhaps, prompt the question of whether - in contrast to all appearances - tiny particles of the dissolved solids are present in solutions. Does such an assumption, however, lead one to believe that the solids before being divided are made up of (preformed) particles - perhaps those which were suspected in the solutions? Are the pupils really ready to go from a - plausible - discontinuous structure of a mixture[+)] (e.g. a sugar solution) to a discontinuous structure of one of the mixture's components (e.g. a sugar crystal)? Do the pupils infer from the - plausible - existence of discrete particles in the mixtures the existence of these separate particles in one of the mixture's components?

(3) The Approach via the Evaporation of Liquids

This approach prompts similar considerations to those raised by the approach via dissolution. Observation of the evaporation of water, for example, can perhaps lead one to believe that tiny particles break away from the water's surface and are dispersed in the air, i.e. that water vapor is discontinuously structured. But are the pupils also ready to draw the conclusion that these particles of the water vapor are already preformed in water and that they are conserved separately during the condensation of water and do not "merge" into a continuum?

When one is trying to lead the pupils to the atomic hypothesis via a mental division of given portions of substance - be it a mechanical division or division by means of dissolution or evaporation - one may not ignore another problem: such a mental division perforce leads the pupils to the conception that the smallest possible subdivisions are small pieces of substance with all the properties of the initial substance. And yet it is a fundamentally important statement of the

+) "discontinuously structured" in this context must not necessarily mean that there are gaps, empty spaces, in the mixture but that the components of the mixture do not merge.

atomic hypothesis that atoms have no substance properties such as density and boiling temperature (but quantity properties such as mass and volume. See J. WENINGER, 1964/65 and 1976).

(4) The Approach via Diffusion

This approach is used in the teaching system of A. KEMPER and R. FLADT (1970, chapter 2.1.):

"One pours ether on a large beaker cover or a glass plate without saying what liquid one has poured. Soon, those sitting in the vicinity will reflect, what liquid has such an odor or will recognize the odor. Now one raises the question of how the ether vapor reached the students. There are two possibilities (which the teacher must name):

The ether spreads in the shape of a compact cloud.
The ether permeates the air.

The latter possibility would involve presupposing that there are gaps in the air".

A problem is touched upon here which also played a large role in the history of the conception of the atom: Is motion without the assumption of space feasible? K. LASSWITZ (1963, I, 107) tells us in his history of atomism that Aristotle dealt with the problem as follows:

"The atomists wanted to justify the assumption of empty space by saying that motion would not be possible without it; namely, spatial motion and the motion of increase can not take place without emptiness because what is full can not possibly take in the moving body or a new body. But the motion can also be explained without the assumption of emptiness since the parts can evade each other; one body leaves the space into which another one enters."

It may be questioned here whether our modern-day pupils are not also more favorably disposed to such a conception of the motion of a (divided or undivided) substance such as ether vapor through another substance such as air. All of the pupils have experienced that, for instance, stones can fall through water without there being any gaps in the water. The stones create such gaps themselves. The same could be true for ether vapor.

My critical remarks are not intended to show that the hypothesis of the discontinuous structure of matter can not conclusively be derived from, or proven by, the described approaches. There is no approach which is capable of that. The atomic hypothesis can only be proposed speculatively. In order to do this, however, the pupils should be confronted with phenomena for whose interpretation a discontinuum hypothesis seems preferable to a continuum hypothesis. The question is whether this is true for the phenomena described. These phenomena could certainly back up a discontinuum hypothesis if the pupils have already formed such an idea. But if the pupils adhere to the continuum hypothesis can these phenomena awaken a readiness to question their own conceptions? Can they trigger a rethinking process as radical as the one necessitated by the atomic hypothesis? The hypothesis that matter is made up of atoms is a fundamental one. It should not be evolved with the aid of phenomena which pupils sooner interpret spontaneously by means of the continuum hypothesis.

3. PIAGET's and INHELDER's Studies of the Development of Atomism in Children

J. PIAGET and B. INHELDER (1969) conducted very thorough studies in which they reach the conclusion that during the intellectual development of the child "atomism" develops spontaneously. PIAGET and INHELDER questioned children between the ages of 4 and 12 (among other things) about

the dissolution process, i.e. a phenomenon which is often used to introduce the atomic hypothesis. The children put lumps of sugar in glasses filled with water. Previous to this experiment they were asked to say whether the sugar would be conserved with respect to its substance, weight and volume. After performing the experiment they were asked to explain the findings. PIAGET and INHELDER found that the youngest children predict a disappearance of the substance, the weight and the volume of the lump of sugar during dissolution. With increasing age the children first assume the conservation of substance, then - in addition - the conservation of the weight and finally also the conservation of volume. The order in which the conceptions of conservation occur is always the same. For our purposes it is interesting that a small percentage of the children who predict a conservation of weight but not volume, and a greater percentage of the children who already predict a conservation also of volume, uses a particle concept to explain this conservation. These children reason as follows: the grains of the lump of sugar do not change either their weight or volume during dissolution. They are merely displaced. That is why the total weight and total volume of the lump of sugar is conserved during dissolution. According to PIAGET and INHELDER, children mentally construct systems made up of inalterable particles with varying compositions in order to justify an invariance of weight and volume (which - with increasing age - are conceived as a priori logical necessities).

It seems to me that the studies of PIAGET and INHELDER give no indication of the conception the subjects had of the structure of the dissolving substance - in this case, the structure of sugar. This is not at all the purpose of the studies. The children observe how a lump of sugar (which - as can be seen macroscopically - is made up of small granules) decomposes into these grains, how the grains become ever smaller until finally nothing is left to be seen. Now when some of the children, stimulated by this observation and to justify an invariance of weight and volume (possibly

assumed a priori) postulate the conservation of minute, invisible sugar granules, it can certainly not be concluded that these children also assume sugar to be made up of such - preformed - granules. The children's answers provided by PIAGET and INHELDER give no indication of whether the children think that the invisible particles presumed to be in the solution are also presumed to be contained separately in the granular lump of sugar. Nor is there any information provided as to whether the children assume that these particles would also be conserved during the formation of a homogenous crystal of sugar, e.g. a piece of rock candy. It is precisely that which would interest us here however.

PIAGET and INHELDER report that children, starting from a particular level of development, also use a particle concept to explain other phenomena: expansion of a maize seed and of a column of mercury when being heated or differences of the density of substances such as cork, wood and pebbles. The quoted responses of the children do not seem to provide a clear indication here either that the children are thinking of the existence of preformed particles.

4. Investigations in Pupils' Pre-instructional Conceptions about Evaporation and Condensation, Dissolution and Crystallization

With my preceding remarks, I am trying to say that it is necessary to record empirically the pupils' conceptions of some of the phenomena which are often used to introduce the atomic hypothesis, particularly with respect to the question of the preformation of the assumed particles.

4.1. Aims of the Studies

The studies described here concern conceptions which pupils develop, prior to their introduction to the atomic hypothesis, of the evaporation and condensation of water and of the dissolution and re-formation of copper vitriol crystals. The

interest of the studies centered among other things on the question, what percentage of the interviewed pupils develops one of the following three conceptions:

(1) Water or vitriol crystals are *continua*. During evaporation or dissolution the continua are "thinned". During condensation or crystallization they "thicken" again.

(2) Water or vitriol crystals are *continua*. During evaporation or dissolution the continua are broken down into *tiny particles which are not preformed*. During condensation or crystallization these particles re-combine and "fuse" with each other to continua.

(3) Water or vitriol crystals are *discontinua*, that is, composed of preformed particles. During evaporation or dissolution the discontinua are broken down into *preformed particles*. During condensation or crystallization these particles re-combine without being "fused" with each other.

It was not a main aim of the studies to find out ready-made conceptions waiting to be recalled at any time. According to W. JUNG (1978), that would be a task almost impossible to carry out: conceptions are developed, augmented, differentiated; specified and changed for many reasons, some of which may occur unplanned in the world outside of school, planned in instruction but also in studies intended to uncover conceptions. It would hardly be possible to ascertain whether a conception already existed or was developed during the study. The only thing that can be deduced is the willingness to react to a situation in one way rather than another. Such a willingness is also important for instruction: it is important for the teacher to know what conceptions the pupils are willing to develop (or even just to accept) when they deal with certain factual and communication phenomena.

The studies did not deal only with the above-mentioned questions but also with methodological problems. They were therefore more extensive than would have been necessary to answer the contentual question alone.

4.2. Preliminary Studies in classroom Conversations

The first studies were conducted in several 7th and 8th grades of "Realschule" by E. KIRCHER and me in conjunction with some teachers. The cooperating teachers inserted special sections into routine science instruction in which the corresponding experiments were performed and discussed. This method was subsequently pursued further by E. KIRCHER (E. KIRCHER, 1980).

4.3. Interviews as Part of the Studies

In the continued investigations several group interviews were conducted first and then a larger number of individual interviews. The greater part of the interviews was conducted by F. GRÜTZMANN (1980). The rest were done by me.

4.3.1. Pupils Interviewed

F. GRÜTZMANN questioned a total of 49 pupils in individual interviews:

19 primary school pupils,	3 grammer school pupils, 7th grade
14 primary school pupils,	3 grammer school pupils, 8th grade
10 primary school pupils,	9th grade

I questioned 12 grammer school pupils (of the 5th to 8th grades).

The 14 primary school pupils of the 8th grade had already worked with a particle model to explain the melting process. The other pupils had not yet been confronted with a particle model during science instruction.

4.3.2. Structure of the Interviews

Every pupil was interviewed three times:

(1) One of the interviews dealt with the evaporation and condensation of water. Water was heated in a porcelain dish. The escaping water vapor condensed on a glass plate which was held over the porcelain dish.

(2) A second interview concerned the dissolution of copper vitriol crystals. First the pupils dissolved a large flat crystal in a petri dish with water, and then other small crystals.

(3) A third interview covered the formation of copper vitriol crystals. The pupils left the solutions created in the preceding interview standing open for a few days and observed the formation of the crystals.

The interview on evaporation and condensation was partly conducted prior to and partly subsequent to the interviews on dissolution and crystallization.

For the individual interviews, guidelines were used which were developed on the basis of experiences with group interviews. The interviews began with a phase in which the pupils performed the experiment and were able to comment freely on the observed phenomena. After that they were given ever more precisely described conceptions between which they were to choose and give a reason for their choice. This procedure corresponded to the aim of not seeking only ready-made conceptions but above all to uncover a willingness to select one of the three conceptions mentioned and use them to reason with. Each interview contained the following segments:

(1) Performance of the experiment and observation of the occurences by the pupil,

(2) Free verbal statements by the pupil: description of observations, comparison with familiar processes, interpretations, questions,

(3) selection of comparisons from comparisons provided,
reasons for the choice,
the pupils' own comparisons,

(4) drawings done by the pupils,
explanation of the drawings,
selection from drawings provided,
reasons for the choice,

(5) selection of interpretations from interpretations provided,
reasons for the choice,
the pupils' own interpretations.

The order of the segments was disregarded whenever the pupils' comments made another order more promising. Each interview took 20 to 30 minutes, not counting the time needed for the experiments.

The appendix (p. 24 f.) contains the comparisons, drawings and interpretations provided in the interviews.

Originally it had been planned to prepare questionnaires later on the basis of the interview guidelines. These questionnaires might have been able to be used in a more extensive written survey. Judging by our experiences with the interviews, such a written survey did not seem to us to be expressive enough any more. Many comments of the pupils can only be interpreted satisfactorily when additional information is gleaned from the conversation.

4.3.3. Difficulties Regarding Conducting the Interviews

Numerous difficulties had to be surpassed with respect to the interviews, particularly at the beginning.

The first studies showed that the pupils observed the old familiar processes with a great deal of interest, but that these processes did not seem to them to be in need of interpretation (with the exception of the formation of vitriol crystals to some extent). Some inducement was necessary to arrive at the explanation level which was interesting for us. The comparisons provided proved to be very helpful here. They stimulated thought processes without channeling these processes too greatly already. They prompted questions, misgivings and suggestions for changes - seldom complete approval. The pupils often justified their choice from among the comparisons using quite different criteria from those which we had in mind. It was not, therefore, the choice itself which was crucial to evaluation but the justification for this choice. Most of the remarks made by the pupils about the comparisons were very informative, going far beyond the sphere encompassed by the investigations.

Initiation into the more strictly controlled sections of the interviews with the aid of relatively open comparisons was a means of surpassing another difficulty which looms particularly large in investigations regarding the conception of the atom: the pupils have already heard about atoms prior to instruction. However, in many cases the acquired information is hardly integrated into their stock of conceptions. When one begins the investigations immediately with very pointed questions there is the danger that only a knowledge of words is prompted. The underlying conceptions are not revealed.

It was extremely important to continuously ascertain whether a pupil moved on a macroscopic or submacroscopic plane in the course of his interpretations.

4.4. Results of the Investigations

Figure 1 contains the results of the individual interviews conducted by F. GRÜTZMANN. My own interviews led to similar findings.

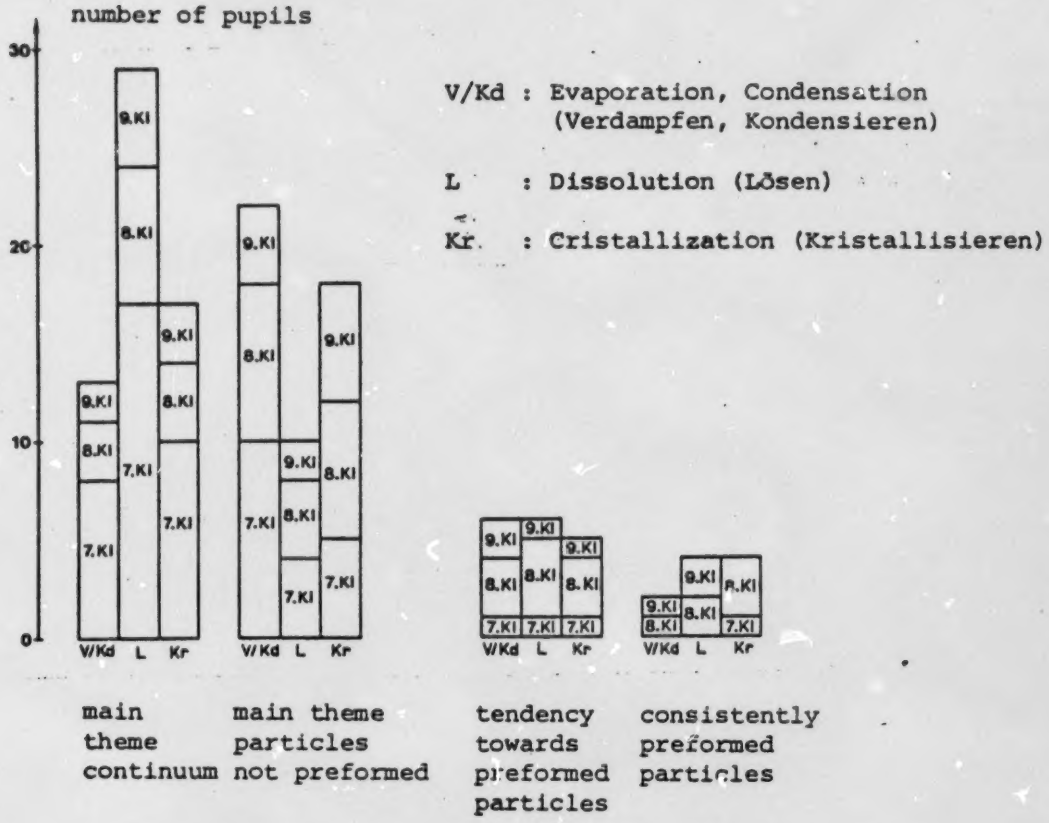
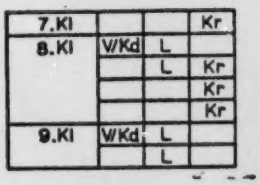


Fig. 1: Number of pupils and their conceptions.
See text for explanation of the figure.



V/Kd : Evaporation, Condensation
(Verdampfen, Kondensieren)

L : Dissolution (Lösen)

Kr : Cristallization (Kristallisieren)

Fig. 2: Distribution of consistent interpretations using the conception of preformed particles among the individual pupils and processes.
See text for explanation of the figure.

4.4.1. The number of Pupils with a Consistent Conception of Preformed Particles

As the diagram shows, only 2 pupils out of 49 consistently (with regard to the comparisons, drawings and interpretations) explained the evaporation and condensation of water using the conception of preformed particles[+]. 4 pupils interpreted the dissolution of the vitriol crystal by means of such a conception and 4 pupils, crystallization. Not one single pupil interpreted all 4 observed processes consistently by means of this conception. And only one pupil used the conception of preformed particles to interprete both dissolution and crystallization (but not evaporation and condensation). Figure 2 shows how the consistent explanations by means of the conception of preformed particles is distributed among the pupils and processes.

4.4.2. The Inconsistency of the Discovered Conceptions

Only those pupils are mentioned above who dealt consistently, in some measure, with the conception of preformed particles. An essential finding of the investigations is the fact that a great number of the interviewed pupils was more or less *inconsistent* in their reasoning. This inconsistency often caused problems in the evaluation and worried us especially at the beginning of the investigations since we assumed them to be the result of flaws in our interviews: had the pupils used completely different criteria from their stated to choose between the comparisons, drawings, explanations? Had we misunderstood the pupils' reasons for their choice? Particularly the comments of the younger pupils were often not easy to interpret. These pupils were not so mindful of their choice of words. Some of the older pupils, however, were extremely careful to put even the smallest nuances of their conceptions into words, to fit their words as precisely as possible to their conceptions. This linguistic differentiation certainly also expresses a differentiation of conceptions.

An impressive example of inconsistent reasoning was found during pre-investigations in an 8th grade of the "Realschule". The pupils, already familiar with the atomic hypothesis tried tc use this hypothesis to explain the

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[+] 6 students could not be incorporated due to inconsistencies.

expansion of air. They had assumed that spherical atoms placed increasing distance from one another. A sketch of the spherical atoms - at first, close to one another and later on, further apart - was to be seen on the blackboard during almost the entire lesson. At the end of the lesson the teacher asked - no longer in connection with the explanation of expansion - after the shape of the atoms. The answers: perhaps hexagonal, sort of alveolate, perhaps even square. In any case, so that they fit together without gaps. None of the pupils noticed that they had previously assumed a spherical shape. These pupils altered their conceptions to suit their needs.

Such an alteration of conceptions is also evident in the finding that some pupils explained crystallization by means of one conception and dissolution by another. Some pupils, for example, assumed a thinning of a continuum to explain dissolution. However, a few days later, when they were supposed to explain the recovery of crystals from the solution, the same pupils assumed that small granules convened in the solution.

In the face of these examples it becomes clear how easily one is led to draw the wrong conclusions during such investigations. If one approaches the conceptions from one single angle, one possibly acquires very satisfying, unequivocal findings. A more differentiated approach can alter the picture considerably.

Concerning the evaluation, in all cases where inconsistency came up, a main theme in the reasoning was sought. It is obvious that leeway in such cases is great. In figure 1, for the continuum conception and for the conception of not preformed particles, the number of pupils is provided who developed a main theme here or a neighboring variant of these conceptions. As far as the conception of preformed particles is concerned, the diagram was more differentiated: for one thing, the number of pupils is provided who worked to some degree consistently with this conception and, for

another thing, the number of pupils who did not pursue the idea of preformed particles consistently but tended towards that direction.

4.4.3. Conception Variants

Some conception variants came up in the course of the interviews. The two most frequent ones will be mentioned here.

Pupils who imagined water and water vapor (or the mixture of water vapor and air), the vitriol crystal and the vitriol solution as being continua developed two different variants to explain the evaporation and dissolution processes. These variants were also found by PIAGET and INHELDER (1969):

(1) the conception of a continuous thinning

(2) the conception of division into not preformed particles with the subsequent complete "dissolution" of these particles ("At first there are still particles in the water. Later on they dissolve completely").

These two conceptions, whose beginning and end points are the same, were treated as a continuum conception during evaluation.

A second conception variant touches upon a problem which kept coming up in the interviews on the dissolution and reformation of blue vitriol crystals: the problem of color. Some of the pupils apparently imagined the blue color without a "carrier" substance. The color appears as a non-substantial addition to the crystal or the solution. Other pupils did imagine the blue color as being connected with a "carrier" substance but this "carrier" substance was kept distinctly apart from the actual substance of the vitriol crystal which was assumed to be colorless. Some pupils also imagined it as acting differently: whereas the colorless substance of the vitriol crystal breaks down into particles during dissolution, the blue "carrier" substance was supposed to thin continuously and "melt" with the water.

5. Conclusions

In the course of the investigations, some classroom conversations and interviews were conducted on the diffusion of ether and on the change of the volume of a given portion of air upon temperature change. The findings point in the same direction as the findings already described.

In view of the uncertainty with respect to assignment to the different explanation possibilities, no more differentiated conclusions should be drawn from the quantitative information. What does follow reliably from the investigations - besides a wealth of qualitative findings which are not described here - is this: only a small number of pupils decides to use the conception of particles, preformed in the substances, in some degree consistently to explain some of the observed phenomena. The majority of the pupils reasons more or less consistently using the conception of substances as continua which either thin continuously or which are broken down into not preformed particles.

The inconsistency in argumentation of pupils who certainly have consistent conceptions in other spheres seems to me to indicate that the pupils had hardly developed any conceptions previously to explain evaporation and condensation, dissolution and crystallization. Such conceptions were gradually formed during the interviews when the pupils were confronted with the phenomena and the provided interpretations.

If pupils hardly bring any conceptions with them of the observed phenomena and spontaneously develop the conception of a continuous structure of substance rather than a discontinuous one, then the observed phenomena seem hardly suited to serve as an introduction to a hypothesis as fundamental as that of atomic structure. These phenomena do little to help the pupils to dissociate themselves from the conception of a continuous structure of substance. Certainly most of the pupils will learn to work with a discontinuum conception

during instruction anyway. However, the question is whether this conception is so tightly anchored that it outlasts school instruction. The first results from investigations which I have begun to conduct on adults indicate that they have similar conceptions as the interviewed pupils: the conception of substances as continua which either thin continuously or can be broken down into not preformed particles.

It is sometimes argued that one should use as many such phenomena as possible to introduce the atomic hypothesis. I consider it improbable that pupils gradually arrive at a discontinuum conception which is really integrated in the other conceptions on the basis of numerous phenomena which, taken separately, all suggest a continuum conception.

6. Other Approaches to the Atomic Hypothesis

Are there more convincing approaches to the atomic hypothesis? The laws of mass, by means of which the atomic hypothesis is often introduced in chemistry instruction, can certainly suggest the conception of preformed particles. This approach, however, is often very tedious for pupils and teachers. The atomic hypothesis can also be reached via more intensive work with the shape of the crystals of various substances (cf. e.g. W. DIERKS, 1965).

Another approach, which is described in the IPN course called "Stoffe und Stoffumbildungen" ("Substances and changes of substances"), uses a basic chemical problem for which in the course of history new solutions were always being sought (J. WENINGER, 1964/65; J. WENINGER, H. PFUNDT et al., 1979): when a new unified substance is formed from two initial substances all properties of the initial substances disappear, i.e. the initial substances can no longer be perceived in the end product. Despite this, they can be recovered from the end product with all their original properties. For instance, red shiny copper and colorless oxygen can be "extracted" from black copper oxide although they are not perceptible in it. In view of the disappearance and origination of substance properties, how can the reversibility of substantial processes be explained?

The reversibility of substantial processes seems to demand something which outlasts all changes. Thus, the question is: what is conserved during the formation of a new unified substance from two initial substances so that the recovery of the initial substances becomes understandable? What changes so that it becomes understandable why the properties of the two initial substances can not be perceived in the end product?

This conflict between change and invariance can be solved with the aid of a discontinuum conception, the conception of substances as particle systems: when substances are considered as systems of unalterable particles, it is the particles which outlasts all change. And it is the configuration, the structure, which can be destroyed and re-created. In the same way that the pieces of a mosaic can be rearranged to form an entirely new picture in which the old picture is no longer apparent, from which, however, the old picture can be reconstructed, the particles of a substance can be rearranged to form a completely new substance in which the old substance is not apparent, but from which it can be recovered.

7. References

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Appendix

In the following the comparisons, drawings and interpretations are provided which were offered to the pupils in the later sections of the three interviews (see p. for the structure of the interviews). These offerings are based mainly on the pupils' comments and were slightly altered several times during the investigations.

The offerings imply:
- in the first case, a continuum which can be thinned
- in the second case, a continuum which can be broken down into not preformed particles
- in the third case, a discontinuum which can be decomposed into its preformed particles.

The interview on "Evaporation and Condensation of Water"

Provided comparisons[+)]

When water evaporates it is like

( ) air when it expands and becomes very thin[++)]

( ) perfume when it is sprayed very finely through a nozzle

( ) a pile of sand when it is whirled apart

[+)] See p. 15 for comments on the function of the comparisons and on the evaluation of remarks about the comparisons.

[++)] The comparisons which imply a continuum conception are all necessarily contestable; according to the atomic hypothesis, there is no substance which is not a discontinuum. The reasons the students gave for their choice of comparisons generally indicated whether the comparison was understood in the sense of a continuum conception or not. These reasons, not the choice itself, were crucial for the evaluation.

When water vapor reverts to fluid water it is like

( ) liquid wax when it solidifies[+)]

( ) dust particles of lead when they are fused

( ) grains of flour when they stick together

Provided Drawings

Provided Interpretations

( ) When water evaporates it becomes very thin, almost like air. When the vapor cools off, it contracts.

( ) When water evaporates it is broken down into tiny invisible drops or particles. The particles are given off into the air. When the vapor cools off, the particles re-combine and fuse with each other.

( ) Water is not as smooth as it seems. It consists of innumerable tiny drops or particles. When water evaporates, the particles are loosed and are given off into the air. When the vapor cools off, the particles re-combine. They do not fuse completely with each other.

+) See preceding footnote.

The interview on "Dissolution of a Crystal of Vitriol"

Provided comparisons[+)]

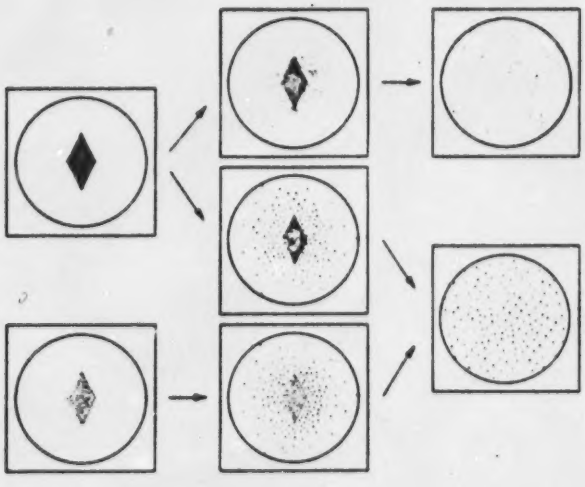
When the vitriol crystal dissolves, it is like

( ) a drop of red cabbage broth when it melts in water[+)]

( ) a piece of rock candy when it is ground into powdered sugar

( ) a lump of sand when it disintegrates

Provided Drawings[++)]



Provided Interpretations

( ) the vitriol crystal thins increasingly and dissolves into the water

( ) the vitriol crystal is broken down into innumerable tiny granules. The granules are distributed throughout the water.

[+)] See footnotes on page 24.

[++)] Separate cards were used for the provided drawings so that each pupil was free to combine them as he pleased.

( ) the vitriol crystal consists of innumerable tiny granules. In water it decomposes into these granules. The granules are distributed throughout the water.

The interview on "Formation of a Vitriol Crystal"

Provided Comparisons[+)]

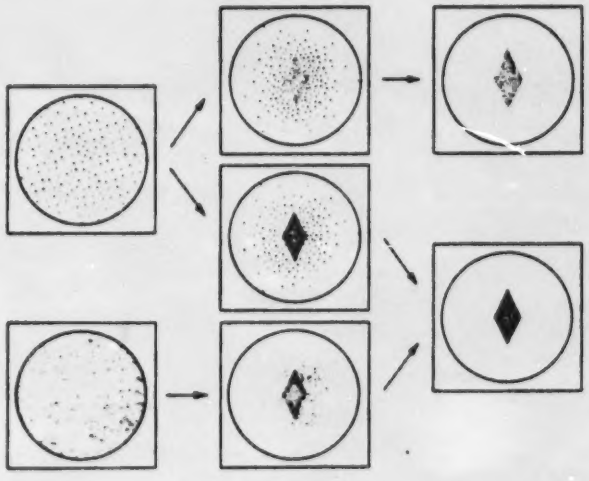
When a vitriol crystal forms in the solution it is like

( ) jelly when it gels[+)]

( ) granules of iron when they fuse to form a piece of iron

( ) pieces of a puzzle when they are put into place

Provided Drawings[++)]



Provided Interpretations

( ) The vitriol has become very thin during dissolution and fused with the water. When the water evaporates the vitriol contracts. This results in crystals.

[+)] See footnotes on p. 24.

[++)] Separate cards were used for the provided drawings so that each pupil was free to combine them as he pleased.

When the vitriol has dissolved completely, innumerable tiny granules float in the water. When the water evaporates, the granules re-combine.

( ) The granules fuse to form crystals.

( ) The granules do not fuse completely in the crystals.